A Sequence of Multidisciplinary Engineering Laboratory Courses

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1 Introduction

1.1 Background

Colorado School of Mines (CSM) is a public research university devoted to engineering and applied science that has distinguished itself by developing high-quality graduates and scholarship. The U.S. News and World Report Inc. rated CSM 26th in the Top National Public Universities and 50th in the Best Undergraduate Engineering Programs with Ph.D. Programs in 2001. The school’s role as written in the Colorado statutes focuses on “energy, minerals, and materials science and engineering and science fields.” The sequence of multidisciplinary laboratory courses described herein lies within the engineering focus and is taught within the Engineering Division.

The Engineering Division is the largest program at CSM with approximately 850 undergraduate majors and 70 graduate students. This population represents a shift from the CSM’s historical earth science and engineering focus. The undergraduate program is an ABET accredited, non-traditional, interdisciplinary, Bachelor of Science Degree in Engineering with specialties in civil, electrical, environmental, and mechanical engineering, as well as graduate degrees (M. S., M. E. and Ph. D) and research in engineering systems. The Gourman Report ranks the CSM Engineering Division fifth among general engineering programs. Primary goals of the program are to provide students with a solid foundation in engineering fundamentals, the skills to adapt to rapidly changing and advanced technologies, and an aptitude for life-long learning. Uniqueness of the program is particularly evident with respect to its multidisciplinary span, heavy experimental component, large credit-hour requirement, and use of advanced technologies.

We recently replaced three traditional, closed, theory-verification laboratory courses in electrical circuits, fluid mechanics, and stress analysis with the Multidisciplinary Engineering Laboratory (MEL) course sequence. Two key words in the title of this paper relay the uniqueness of the MEL approach: “multidisciplinary” and “sequence”.

1.2 Sequential Laboratory Courses at Other Universities

Several universities teach sequential laboratory courses focused on topical depth. For example, Texas A&M University connected a course in microprocessors and a course in electronic interfacing in a sequence. Both have three hours of recitation and two of laboratory each week.
In another example, Branner\textsuperscript{5} describes a sequence of three, four-credit hour courses including laboratories in the Electrical Engineering and Computer Science Department at the University of California at Davis. The sequence is taught to seniors and first-year graduate students during the, fall, winter, and spring quarters. The purpose of the sequential courses is to provide an in-depth understanding of microwave theory, circuits, and applications. The laboratory experiments provide hands-on experience with theory taught in class and introduce students to instrumentation used in industry. The laboratories include projects where students complete paper design, computer analysis, circuit layout, circuit fabrication, testing, and a report.

Engelken\textsuperscript{6} described a sequence of two laboratories in semiconductor materials and devices in the Department of Engineering at the Arkansas State University. The courses complement three lecture courses in semiconductor materials, devices, and optical electronics. The laboratory courses require six contact hours per week. The first course is three credit hours and the second is two credit hours. The laboratory is divided into activity sets where each set lasts four class periods. Three experiments compose each set since the courses use a team within a team format where each small team completes one of three experiments and presents and shares the results with the larger team. Initially, step-by-step procedures are used, but students graduate to “research” activities in the second course. Engelken related two problems; their department doesn’t have graduate students and the experiments require one-of-a-kind expensive equipment.

Arizona State University adopted a consistent and integrated set of laboratory facilities for a three-semester digital systems design sequence.\textsuperscript{7} Consequently, students learn the use of laboratory software and hardware sequentially. This was found to be more effective than using different equipment in each of the three laboratories and asking students to re-learn different software and hardware.

1.3 The Unique Educational Objectives of the MEL Course Sequence

Like the examples above, the main focus of most laboratory sequences is subject matter depth; however, MEL has a longer list of objectives (shown in Table 1) that are developed sequentially. These objectives fit the goals of the broad engineering degree in the CSM Engineering Division, and they are applicable to many other undergraduate engineering programs, especially those desiring ABET accreditation. MEL’s educational objectives are focused on experiments that integrate multiple subjects. The outcome is to prepare graduates that can integrate multiple disciplines, extend their knowledge to new topics over their professional lifetime, be team and project leaders, and implement instrumentation in engineering projects and products.
Table 1. MEL Educational Objectives.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Enhance thinking skills.</td>
</tr>
<tr>
<td>2</td>
<td>Integrate knowledge from several courses.</td>
</tr>
<tr>
<td>3</td>
<td>Emulate industrial practice by using a systems and applications context.</td>
</tr>
<tr>
<td>4</td>
<td>Build subject matter competency in fundamental engineering topics.</td>
</tr>
<tr>
<td>5</td>
<td>Actively learn the skills of efficient and accurate experimenters.</td>
</tr>
<tr>
<td>6</td>
<td>Improve student retention of laboratory/experimental skills and hardware.</td>
</tr>
<tr>
<td>7</td>
<td>Build life-long learning skills.</td>
</tr>
<tr>
<td>8</td>
<td>Experience a variety of learning styles.</td>
</tr>
<tr>
<td>9</td>
<td>Enhance group and teamwork skills.</td>
</tr>
<tr>
<td>10</td>
<td>Enhance communications skills.</td>
</tr>
</tbody>
</table>

1.4 Challenges

Several major challenges were identified and solved during initial implementation of the MEL course sequence. The first challenge was teaching a uniform curriculum that meets the above objectives to a large number of students (typical enrollment shown in Table 2) in a division where the overall student/faculty ratio is approximately 30. The maximum enrollment is 30 students per section in MEL I and 18 students per section in MEL II and III. The second challenge was developing the facilities to support the MEL sequence in a division that has grown from 150 to over 850 undergraduates over the last 20 years with little increase in physical space. The third challenge was writing new experiments with exploratory pedagogy, combining them into three published laboratory manuals, and developing a course web site. The fourth was training instructors and graduate teaching assistants to mentor and coach the educational processes that would lead to fulfilling the objectives. The fifth challenge was developing new, inexpensive, reliable experimental equipment to support discovery-based multidisciplinary experiments.

Table 2. MEL Enrollment in the 2000-2001 Academic Year.

<table>
<thead>
<tr>
<th>Laboratory Course</th>
<th>Fall 2000</th>
<th>Spring 2001</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sections</td>
<td>Enrollment</td>
</tr>
<tr>
<td>EGGN 250 (MEL I)</td>
<td>5</td>
<td>146</td>
</tr>
<tr>
<td>EGGN 350 (MEL II)</td>
<td>6</td>
<td>65</td>
</tr>
<tr>
<td>EGGN 450 (MEL III)</td>
<td>2</td>
<td>22</td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>233</td>
</tr>
</tbody>
</table>

2 Sequential Integration of Knowledge Across Multiple Disciplines

2.1 Implementation

MEL teaches problem solving skills. Therefore, instructors must balance between a “hands-off approach and a traditional explain–all-the-steps approach. An instructor and a teaching assistant (TA) are present in every MEL section to provide mentoring and coaching support to students who are struggling to discover the operation of instruments and develop experimental procedures.
on their own. Some universities may not consider this an effective use of instructional resources, and use step-by-step procedures that students can follow with less mentoring. The courses replaced by MEL used step-by-step instructions, but we concluded that students were just going through the motions to get the information necessary to “fill in the blanks” in a laboratory report and they were not really understanding the material, enhancing their thinking maturity, or becoming life-long learners.

MEL instructors must possess the ability to coach as well as be technically competent. Instructors may be lecturers, adjunct or tenure-track faculty, and often have served in industry. TAs are graduate students in the Engineering Systems program or a related department. A major problem is that MEL is new to our campus and is significantly different from laboratory courses taught at other universities, so our graduate students lack previous experience. Therefore, we provide training for TAs and instructors in coaching to improve thinking maturity. As TAs become more proficient at coaching in MEL, we will reduce the number of lecturers and adjunct professors. For example, one of the sections of MEL II is being taught solely by a graduate TA; however, this TA is exceptional since he took the MEL sequence as an undergraduate and has had two semesters experience as a TA working with an instructor. A professor oversees all instructors and TAs in MEL I, II and III.

Student preparation is a key element of MEL. Before coming to class, each student studies the experiment requirements, reads reference material, and reviews connected material from other courses. They prepare answers to a mandatory pre-experiment report that requires them to model the experiment to predict results and develop a preliminary step-by-step procedure that minimizes time to conduct the experiment and minimizes errors. Each MEL class begins with a 15 to 20 minute introduction by the instructor to focus the students on the task at hand and to answer preliminary questions. Lectures do not give step-by-step instruction on operating instrumentation. Students are expected to discover how to operate new instrumentation using reference materials and cooperative learning. Students then form groups of three, with each team working at their own workbench. The team modifies the procedures the members have written individually prior to coming to class. At the end of the experiment, students individually submit their final procedure as part of a report. The experiments, pre-experiment reports, results reports, and reference material for the MEL course sequence are available in the laboratory manuals\textsuperscript{9,10,11} and on the course website by following the links from the CSM website\textsuperscript{12} to the Engineering Division and to one of the MEL courses (EGGN 250, 350, or 450).

2.2 General Thinking Skills

The MEL experience is designed to sequentially enhance thinking maturity by helping students develop the abilities to\textsuperscript{13}:

- Reduce complex systems to their component parts.
- Accept ambiguity and identify and develop alternative solutions to a problem.
- Assemble components into a structure not clearly there before.
- Make judgments using criteria and evidence.
- Make commitments based on their own judgments, not an authority’s.
It is necessary to enhance thinking sequentially, since students don’t mature within one semester. In fact, there is a wide variety of levels of thinking maturity among the students at CSM. We do not attempt to bring everyone to the same level. We want students to advance from their current level to higher levels at a pace that is challenging but not overwhelming. To enhance thinking maturity, the experiments are designed so students perform the activities shown in Table 3. The required actions are numerous and students in MEL I do not complete them all correctly. However, with continual coaching through the sequence of courses, students are more comfortable and confident with the process in MEL III. Other laboratory courses require students to decompose a problem, but they do not integrate problem decomposition with the other thinking skills.

Table 3. Thinking Maturity Goals and MEL Experiment Required Actions.

<table>
<thead>
<tr>
<th>Goal</th>
<th>Required actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce complex systems to their component parts.</td>
<td>Read experiment requirements, Read reference material, Decompose problem, Develop a procedure in pre-laboratory report</td>
</tr>
<tr>
<td>Accept ambiguity and identify and develop alternative solutions to a problem.</td>
<td>Develop alternative procedural steps, Answer pre-experiment questions on reading, Model experiment in pre-laboratory report, Discover how to use instruments.</td>
</tr>
<tr>
<td>Assemble components into a structure not clearly there before.</td>
<td>Assemble apparatus without instructions</td>
</tr>
<tr>
<td>Make judgements using criteria and evidence</td>
<td>Gather data, Compare data with model, Evaluate and revise procedure, Answer questions in results report</td>
</tr>
<tr>
<td>Make commitments based on their own judgments, not an authority’s.</td>
<td>Defend conclusions to team members and instructors</td>
</tr>
</tbody>
</table>

MEL could not enhance thinking maturity alone. At CSM, this objective is shared in a mixture of courses to emphasize its importance, provide a more coherent educational experience, and be more effective in raising students’ levels of thinking than a non-integrated approach. As shown in blue in Figure 1, students take Design I in the freshman year followed by MEL I and Design II in the sophomore year, MEL II in the junior year, and MEL III and Capstone Design in the senior year. The result is that students receive an introduction to cliented, open-ended problem solving (COEPS) including teamwork, written and oral communications, and project management in Design I and II that is reinforced and extended in the MEL sequence. MEL experiments do not use COEPS like the design courses, or the problem-based laboratories like the CMU Chemical Engineering Undergraduate Laboratory. Our experience indicates students have difficulty applying engineering science fundamentals in COEPS; therefore, MEL experiments are designed to build the thinking skills necessary to effectively apply engineering science fundamentals to COEPS. The experiments are also required for all students, so subject matter competency in multiple areas is provided for everyone and is not project specific.
Figure 1. Typical CSM EG Curriculum Flow Chart (MEL Connections Color Coded).
2.3 Integrating Knowledge from Several Courses

Each MEL experiment requires students to connect concepts from different courses into realistic system experiments that better mimic industry practice. To enhance thinking skills and to simultaneously help students connect engineering science and design, the MEL sequence integrates concepts from many courses by adding a few new course integrations to each MEL course. MEL I begins with simpler and shorter, almost closed-ended experiments. As additional course material is integrated, experiments become more complex, growing to more open-ended projects in MEL III.

MEL I experiments integrate material from electrical circuits, physics and mathematics courses taken prior to or in the same semester shown in red in Figure 1. King et al.\(^3\) gives several examples of experiments that require this multidisciplinary integration. MEL II integrates the MEL I related courses with Strength of Materials, Fluid Mechanics, and Probability and Statistics shown in green in Figure 1. MEL III integrates the MEL I and II related courses with Machine Design, Dynamics, Thermodynamics, and Controls. So as the course sequence progresses, and the students become more proficient in engineering subjects, it becomes more multidisciplinary and experiments integrate a larger amount of material into more sophisticated and realistic systems. The more sophisticated systems require more time to analyze, so the number of experiments completed during the semester decreases from eight in MEL I to five in MEL II and three in MEL III as shown in Table 4.

Thinking skills and subject matter depth become integrated through the MEL sequence. For example, most of the MEL experiments use computer data acquisition systems programmed in LabVIEW. Figure 1 shows that students take C++ in the fall semester of the sophomore year that extends their high-school programming knowledge. Students study and use simple LabVIEW programs written by instructors in MEL I. Most students complete a week-long intensive course in LabVIEW during the field session course (EGGN 233 shown in light blue in Figure 1) during the summer between the sophomore and junior years. In MEL II students write some of their own programs and use some more sophisticated programs written by instructors. In MEL III, students write their own programs. Throughout this sequence, students learn to decompose sophisticated systems problems since as more subject matter is integrated, the systems, and consequently number of sensor inputs and size of programs, grow dramatically.

Writing skills also develop with the sequence. MEL is part of the writing across the curriculum (WAC) program at CSM and integrates written communications material presented in Design I, II and Capstone Design I and II. In MEL I, students write in a laboratory notebook, write short answers on the pre-experiment and results reports, correctly write equations defining symbols and variables, and correctly format graphs for data presentation using the styles presented in the WAC reference text\(^{16}\). They repeat these activities in MEL II, but instead of short answers to questions on the report forms, they write memo reports. In MEL III they produce full engineering reports.
Table 4. Typical Course Schedules for the MEL Sequence

<table>
<thead>
<tr>
<th>Wk</th>
<th>MEL I Topic</th>
<th>MEL II Topic</th>
<th>MEL III Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Thermistors, Voltage Divider</td>
<td>Experimental Stress Analysis</td>
<td>Automatic Proportional Valve Control for Fatigue Testing</td>
</tr>
<tr>
<td>2</td>
<td>“</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>3</td>
<td>Force, Strain, and Bridge Circuit</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>4</td>
<td>“</td>
<td>Materials Analysis</td>
<td>“</td>
</tr>
<tr>
<td>5</td>
<td>Oscillation and Frequency</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>6</td>
<td>Thermal Expansion</td>
<td>Flow Measurement</td>
<td>Refrigeration Cycle Analysis, Diagnostics, and Design</td>
</tr>
<tr>
<td>7</td>
<td>Pressure</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>8</td>
<td>“</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>10</td>
<td>“</td>
<td>“</td>
<td>Vehicle Suspension Analysis and Design</td>
</tr>
<tr>
<td>11</td>
<td>Microphone System, Amplifier, Filter</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>12</td>
<td>“</td>
<td>Wind Tunnel</td>
<td>“</td>
</tr>
<tr>
<td>13</td>
<td>Rotary and Linear Position</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>14</td>
<td>“</td>
<td>“</td>
<td>“</td>
</tr>
<tr>
<td>15</td>
<td>Exam</td>
<td>Exam</td>
<td>Exam</td>
</tr>
</tbody>
</table>

Similar growth occurs in error analysis, diagnostics, and modeling.

The automatic proportional valve control for fatigue testing project in MEL III (Table 3) provides an example of the sequential integration. Students are required to write a professional engineering report that describes the process, errors, and results of automatically controlling a proportional valve from a computer data acquisition and control system to conduct a fatigue test. Students develop a procedure for using the proportional control valve to control fatigue loading of a specimen, write a control program, perform the experiment, evaluate the performance of the valve, and evaluate the procedure. The hydraulic fluid power system is part of a modified Tinius Olsen materials testing machine shown in Figures 2 and 3.
Students use pressure and linear displacement transducers mounted on the machine for control loop feedback. Because we don’t lecture or provide step-by-step procedures for performing experiments in MEL, student teams must:
1. Read reference material \(^9,10,11,17,18,19,20\), ask questions, and experiment with the proportional valve to discover how it operates. Essentially they have to understand how the spool controls pressure and flow and how the spool reacts to different levels of control voltage.

2. Discover how to develop open- and closed-loop control programs in LabVIEW.

3. Determine the frequency, maximum load, minimum load, and waveform shape for completing a fatigue test to failure in a prescribed time period.

In the first part of the experiment, students develop an open-loop control with a potentiometer and power supply. Then, they develop an open-loop control program in LabVIEW. In the third part, they develop a closed-loop control program. In the fourth part they develop a closed loop program that will cycle loading and fatigue a specimen. They have to develop appropriate graphical user interfaces for the programs that include stress-strain and loading-rate graphs. An additional complication is that fluid leaks around the Tinius Olsen cylinder and students’ programs must maintain correct loading and cycling with the pressure-related leakage. Furthermore, the program must reset the spool position to zero anytime the program stops, otherwise the machine continues to load uncontrolled.

To help students write the full engineering report, i.e. continue the writing across the curriculum progression, we omit the pre-experiment report in MEL III. We ask students to write portions of their engineering report describing what they accomplished in the previous week and hand it in at the beginning of each class. We give feedback on technical accomplishment, procedure, and writing. Students make corrections based on our feedback, submit a full report and at the end of each of the three MEL III experiments (see Table 3).

Without prior experience in the MEL sequence, students would not be able to complete the MEL III experiments in the five, three-hour classes available for each. In MEL III, students review their MEL II reports, the MEL II Manual and Reference materials that reinforces MEL II subject matter and concepts. Specifically, students used the Tinius Olsen machines in MEL II to manually control compression and tension tests, developed GUIs with stress-strain graphs, and determined Young’s modulus using the same linear displacement and pressure transducers. Students also review subject matter and concepts from MEL I (that they also reviewed and used in MEL II) like: LabVIEW programming, strain, strain gages, pressure transducers, error analysis and propagation of error, grounding, bridge circuits, single-ended referenced vs. differential measurements, linear displacement, resolution, sensitivity, wiring and circuit diagrams, and diagnostics.

In addition to connecting knowledge from the MEL sequence, students connect knowledge from several courses (see Figure 1) like: Fluid Mechanics (hydraulic fluid power systems), Strength of Materials (Stress-strain graphs, Young’s modulus, and fatigue failure), and Controls (modeling and programming a closed-loop control system).
3 Evaluation/Project Results

MEL was introduced to the curriculum gradually and carefully by first offering a pilot course of MEL I, evaluating it and making modifications before obtaining approval to replace a traditional laboratory course. A similar process was followed later for MEL II, and finally MEL III. King et al. provides full assessment reports. The following sources were used for assessment data:

- Survey Instrument
- Exam Questions
- Independent Evaluator Classroom Observation
- Focus Groups Led by Independent Evaluators
- CSM Student Evaluation Forms
- Alumni Survey

Our initial assessment began with a pilot class of twenty-five students. A group of four senior students started earlier in the semester and stayed one or two weeks ahead of the main pilot group, so our experiments were tested three times before they were used in a required course, once by the professor, once by the seniors, and once by the pilot class. The initial MEL I pilot class was a small section of our traditional electrical circuits laboratory course that was asked to volunteer. The MEL I, II, and III pilot courses were taught parallel to the traditional laboratory courses that were the control group.

3.1 Independent Evaluator Group Assessment of MEL I

An independent assessment team of faculty from other departments at CSM (Dr. Pavelich, Chemistry, Dr. Olds, Liberal Arts, and Dr. Pang, International Studies) used focus groups, classroom observations and a student survey to gather comparative data between MEL and the control group in EGGN 383 (the traditional electrical circuits laboratory). They concluded that MEL I definitely met its goals; it caused more and deeper learning, with obvious integration of topics and student excitement about the experience. However, they were concerned that MEL may be at the extreme end of what students can handle. Specific statements heard by the three assessors were:

- MEL is open-ended, EG383 is cookbook.
- MEL forces critical thinking and deeper learning.
- MEL focuses on how to learn, EG383 on what to learn.
- Only MEL integrates circuits, fluids and strengths.
- MEL students have an excitement about the experience that EG383 students do not.
- MEL is perceived as much more "real-world".
- MEL students use teamwork in a more sophisticated fashion.
- MEL teaching is more Socratic (coaching, not telling).
- MEL open-endedness requires much more teacher time.
- MEL creates a higher frustration level than needed.
- The background supplied at the start of a MEL assignment often seems overwhelming.
• Information may have been incomplete or inaccurate in some MEL assignments.
• Non-Engineering students felt their background was inadequate for MEL and it was inappropriate to their needs.
• There may be too much depth expected or too many assignments for success with less devoted faculty.

3.2 Survey Results

Students also completed a written survey. Table 4 summarizes the results of the question on engineering knowledge and skills where 4 = strongly agree and 0 = strongly disagree.

<table>
<thead>
<tr>
<th>Components</th>
<th>Mean Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>EGNN 383</td>
<td>MEL</td>
</tr>
<tr>
<td>a. This lab requires me to apply knowledge of mathematics, science or engineering.</td>
<td>2.82</td>
</tr>
<tr>
<td>b. I feel that I can apply what I’ve learned in this lab to real world problems.</td>
<td>2.27</td>
</tr>
<tr>
<td>c. My lab class really requires me to think about what I am doing rather than just plugging numbers into formulas.</td>
<td>2.73</td>
</tr>
<tr>
<td>d. This lab teaches me to design and conduct experiments.</td>
<td>2.55</td>
</tr>
<tr>
<td>e. This lab teaches me to analyze and interpret data.</td>
<td>2.73</td>
</tr>
<tr>
<td>f. My lab class is preparing me for higher level engineering courses.</td>
<td>2.18</td>
</tr>
<tr>
<td>g. This lab provides me with the ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.</td>
<td>2.55</td>
</tr>
<tr>
<td>h. I feel confident that I could design an experiment to calibrate a new laboratory or field apparatus or sensor that my future employer might purchase.</td>
<td>1.55</td>
</tr>
<tr>
<td>i. This lab teaches me to solve engineering problems on my own.</td>
<td>2.45</td>
</tr>
</tbody>
</table>

3.3 Independent Evaluator Assessment of MEL II

Our assessment continued during the spring semester, 1998, with MELII. The independent evaluator report concluded:

1. Students refer to traditional labs as “plug and chug” and to MEL as “open-ended”. It was clear that MEL students sometimes wrestled with the fact that open-endedness requires more time and effort on their part.

2. MEL students mentioned that because the lab procedure was not specific that they needed to communicate with their lab partners. Students in traditional labs also communicate with each other, but on a more ad hoc basis.
3. Written communication skills stressed in some traditional labs, but there is not as much opportunity to practice verbal communication skills in traditional labs as there is in MEL labs.

4. MEL students said explicitly that teamwork was more important in MEL than in other labs because one needed to rely on other students to determine the lab procedure.

5. During observation of MEL and traditional labs, MEL students were more consistently engaged in the particular task at hand and with each other.

3.4 Student Evaluation Scores

The students in the course evaluate all courses at the Colorado School of Mines. The administration and faculty committees use the scores as one input of teaching effectiveness in tenure, promotion, and merit raise evaluations. The final report to FIPSE contains details on the analysis of student evaluation scores of all MEL courses from Spring Semester 1977 through Summer Semester 1999. The conclusions from the data analysis were:

In general MEL III scores were the highest, followed by MELII, and MEL I.

The students gave high scores on the following questions:

Work required for amount of credit: A-too much, C-appropriate, E-too little
The instructor meets scheduled classes regularly, except for necessary absences.
The instructor grades and returns assignments and tests within a reasonable time.
Assignments are relevant.
Grading is fair.
The instructor knows the course material.
The experiments are: A-too advanced, B-slightly too advanced, C-about right, D-slightly too simple, E-much too simple
Laboratories have appropriate equipment.
The instructor teaches with enthusiasm.

The students gave average scores to the following questions:

Course material is well presented.
Complex material is well explained.
The instructor accessible.
Assignments are well explained.
This instructor is: A-Not very demanding, B-Moderately demanding, C-Very demanding
This instructor facilitated your learning.
Overall would you consider this instructor: A-Superior, C-Average, E-Poor
The experiments help to understand the principles of the field.
The experiments teach ideas which are useful outside the laboratory.
The experiments help students learn laboratory techniques and procedures.
The experiments stimulate interest in the subject. Laboratory assistants help the student to clarify problems. Laboratories have up-to-date equipment. The instructor tries to clarify concepts and/or help lead students to understand the concepts when students have difficulty. When asked a question in class, the instructor is able to explain the material or concept in different ways, rather than repeating or paraphrasing the original explanation. The instructor shows knowledge of current research appropriate to the course, or uses his experience to amplify or illustrate subject matter. The instructor is willing to discuss and help with student problems outside of class. The instructor challenges students intellectually. Rate this course overall A-Excellent, B-Above Average, C-Average, D-Below Average, E-Poor The instructor encourages creativity. No classroom embarrassment when errors occur. The instructor involves the student in thinking and problem solving. Demonstrations or examples are used to clarify difficult material.

The students gave low scores to the following questions:

The procedures for experiments are clearly described. A well-written Laboratory Manual is used.

As a result of the last statement, we use student and instructor comments to modify the lab manuals every semester.

3.5 Alumni Assessment

Independent evaluators conducted a telephone survey of CSM Alumni who completed one or more of the MEL courses. The following summarizes the responses.

To what extent did MEL mirror what you do in your job?

In general, most respondents used the teamwork skills, open-ended problem solving skills, and knowledge of working with multidisciplinary systems. A few used the technologies taught in MEL.

What worked in MEL, what didn't?

Initially the hardware was not reliable and the course was disorganized, but it improved every semester. After a few semesters, the hardware and experiments for implementing the multidisciplinary concepts seemed to work well. But some students may not have been mature enough to thoroughly comprehend the concepts in MEL I. The laboratory computer systems did not always work as well as they should.

What did you see as the strengths and shortcomings of your MEL Lab courses?
The course was more oriented to real-world applications than traditional laboratory courses. However, non-EG majors were not comfortable with the course, and there seemed to be too much work for the number of credit hours.

3.6 Instructor Observations

Instructor experience in teaching all courses in the sequence provides a couple of insights not available from the other assessment tools. First, MEL I students typically claim that the laboratory equipment is faulty when in fact they have wired the circuit incorrectly and are not yet adapt at diagnosing errors. The number of faulty equipment claims in MEL III is much less, but when students suggest faulty equipment, they are more often correct. Second, students are more confident in MEL III and they are proud of their ability to solve problems on their own. Consequently, they ask fewer questions, but when they ask one, it is more sophisticated, which makes it more difficult for the instructor to help them quickly.

4 Conclusions

A multidisciplinary laboratory course sequence was developed, taught and evaluated in the Engineering Division at the Colorado School of Mines. The three courses are taught sequentially in the sophomore, junior, and senior years. MEL prepares students for their professional careers by providing a more realistic, professional experience through integrating discipline specific components into complete systems and building subject matter depth through a multiple-course sequence. The sequence allows experiments to move beyond basic theory verification to reorganizing knowledge and connecting concepts from several courses.

Independent evaluators concluded that MEL I definitely met its goals of enhancing thinking maturity, integrating knowledge from several courses, emulating industrial practice by using a systems and applications context, building subject matter competency, learning the skills of efficient and accurate experimenters, improving retention, building life-long learning skills, and enhancing teamwork skills. The independent evaluators concluded that MEL caused more and deeper learning, with obvious integration of topics and student excitement about the experience. However, they were concerned that MEL may be at the extreme end of what students can handle.

We found that by sequentially integrating multiple courses, students were able to build increasingly complex and sophisticated multidisciplinary systems that approach those in industrial practice.

Based on the results of implementation, evaluation, and improvement, MEL has become a major focus of the undergraduate program in engineering at CSM. In addition, it became the focus of a recent Program of Excellence award from the Colorado Commission of Higher Education, and MEL received an award from the American Council on Education for enhancing educational quality while controlling cost. Furthermore, CSM has allocated a sizeable piece of a new building, the Center for Technology and Learning Media, to the MEL program, and a proposal to build an addition to the current Engineering Division building (George R. Brown Hall) is being presented to the State, also based on MEL pedagogy and accomplishment.
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